Brake and Tire Wear Emissions in MOVES2014

1 Introduction

The mobile source particulate matter inventory includes exhaust emissions and non-exhaust emissions. Exhaust emissions include particulate matter attributable to engine related processes such as fuel combustion, burnt oil, and other particles that exit the tailpipe. Non-exhaust processes include brake wear, tire wear, suspension or resuspension of road dust, and other sources. Particulate matter from brakes and tires can be created by abrasion, corrosion, and turbulence. These processes can result in particles being suspended in the atmosphere. The size, chemical composition, and emission rate of particles arising from such sources contributes to atmospheric particle concentrations. However, these particles are composed of different species and size than exhaust particulate matter.[1]

2 Brakewear

2.1 Literature Review

There are two main types of brakes used in conventional (or non-hybrid electric) vehicles: disc brakes and drum brakes. In a drum brake, the components are housed in a round drum that rotates with the wheel. Inside the drum are shoes that, when the brake pedal is pressed, force the shoes against the drum and slow the wheel. By contrast, disc brakes use an external rotor and caliper to halt wheel movement. Within the caliper are brake pads on each side of the rotor that clamp together when the brake pedal is pressed.[2]

The composition of the brakeliner has an influence on the quantity and makeup of the released particles. Disc brakes are lined with brake pads while drum brakes use brake-shoes or friction linings. These materials differ in their rate of wear, their portion of wear particles that become airborne, and the composition of those particles. Both types of brakes use frictional processes to resist inertial vehicle motion. The action of braking results in wear and consequent release of a wide variety of materials (elemental, organic and inorganic compounds) into the environment.

The overall size or mass of the brake pads also varies with vehicle type. Typically trucks use larger brakes than passenger vehicles because the mass of vehicle that requires slowing down or stopping is greater. In 2004, most light duty vehicles used disc brakes in the front and drum brakes in the rear. Disc brakes tend to have improved braking performance compared to drum brakes and have correspondingly higher cost is acceptable. Disc brakes are sometimes used on rear wheels as well for higher performance (sportier) vehicles.

As a complicating issue, the particulate matter from brakes is dependent on the geometry of the brakes, wheels and rims. The air flow through the rims to cool the brakes and rotors play a key role in determining the wear characteristics. The emissions are also sensitive to driver activity patterns, where more aggressive stop and go driving will naturally cause greater wear and emissions.

One of the earliest studies on brake wear emissions was done in 1983.[3] Particulate emissions from asbestos-based brakes from automobiles were measured under conditions simulating downtown city driving. The report presented a systematic approach to simulating brake applications and defining particulate emissions, and was used in the development of the EPA PART5 model.[4] For PART5, EPA calculated PM_{10} emission factors for light-duty gasoline vehicles of 12.5 mg/mi for brake wear. Since 1985, the asbestos in brakes has been replaced by other materials, and newer studies have been conducted. These factors suggest the need for this update of the emission factors applicable to more modern vehicles.

In recent studies, Garg et al. (2000) conducted a study in which a brake dynamometer was used to generate wear particles under four wear conditions.[5] The study was performed using seven brake pad formulations that were in high volume use in 1998. Measurements were taken on both front disc as well as rear drum brakes. The study measured mass, size distribution, elemental composition, as well as fiber concentration at four temperature intervals. The reported estimates for $PM_{2.5}$ and PM_{10} for light-duty vehicles ranged 3.4-4.6 mg/mile respectively for small vehicles, and 8.9-12.1 mg/mile respectively for pickup trucks.

Sanders et al (2003) [6] looked at three currently used classes of lining materials: low metallic, semi-metallic and non-asbestos organic (NAO) representing about 90% of automotive brakes at that time. Three kinds of tests were conducted: a dynamometer test, a wind tunnel test and a track test at the Ford Dearborn proving grounds. Tests were done using three different lining type/vehicle combinations that were representative of a wide range of current light-duty vehicles. Three sets of brake conditions were used: (a) urban driving program (UDP) with a set of 24 stops for the dynamometer test and (b) a series of high speed 1.8 m/s^2 stops of a mid-size sedan with low metallic brakes in a wind tunnel and c) measurements of same vehicle on a test track where decelerations were made from 60 mph at 0.15, 0.25 and 0.35 g, the latter being quite aggressive (corresponding to -7.9 m/s called the AMS test). The authors found that the mean particle size and the shape of the mass distribution are very similar for each of the three linings, however they found that the low metallic linings generate 2-3 times the number of wear particles compared to semimetallic and NAO linings. They also found that wear increased non-linearly with higher levels of deceleration. Wear debris composition has the highest concentration of the elements Fe, CU ,Si, Ba, K and Ti, but the PM composition varies by brake type. The authors further found that 50-70% of the total wear material was released in the form of airborne particles.

Table 2-1 contains the emission rates derived from the literature review conducted in support of MOVES2009.[7]

Table 2-1 - Non-Exhaust PM Emissions from Mobile Sources Literature Values of emission factors for break lining wear

Literature Source	Vehicle Type	$PM_{2.5}$ [mg/km]	PM_{10} [mg/km]
Luhana et al.(2004)	Light Duty		6.9
	Heavy Duty		49.7
Sanders et al (2003)	Light Duty		1.5 -7.0
Warner et al. (2002)	Passenger Cars		9
	Light Duty	0 - 5	0 -80
Abu- Allaban et al.(2002)	Heavy Duty	0-15	0-610
Westurland, K.G. (2001)	Light Duty		6.9
	Heavy Duty		41.2
RAINS model (2001)	Light Duty	2.2	3.6
	Heavy Duty	7.1	22.8
Garg, et al(2000)	Passenger Cars	2.1	2.9
	Large Pickup Trucks	5.5	7.5
Cadle et al (2000)	Small Cars	1.8	2.9
	Large Cars	2.8	4.5
	Trucks	4.8	7.6
	Passenger Cars		1.0
Annette Rauterberg-Wulff (1999)	Heavy Duty		24.5
	Vehicles		
Carbotech(1999)	Passenger Cars		1.8
	Light Duty		4.9
	Heavy Duty		3.5
Cha,et al.(1983)	Cars and Trucks		7.9

2.2 Developing Rates for MOVES

2.2.1 Emissions during braking

The MOVES2009 emission rate averages the contributions of:

(1) Composition of brake pad
(2) Number (and type) of brakes
(3) Front vs rear braking
(4) Airborne fraction

and explicitly accounts for:

(1) Particle size distribution (PM2.5 vs PM10)
(2) Braking intensity
(3) Vehicle class: Light-Duty vs Heavy-Duty

As discussed in Sanders et al. (2003), most brake pads are either low-metallic, semi-metallic (full-truck),or non-asbestos organic (full-size car). Using the results from Sanders et al. (2003), we make the following assumptions which are consistent with those used in the paper.

- equal mix of the three brake types,
- four brakes per light duty vehicle, including 2 front disc brakes, and 2 rear drum brakes
- 2/3 of braking power in front brakes (1/3 rear)
- the fraction of total PM below 2.5um is ~ 10% (+/-5%)
- 60% of brake PM is airborne (+/- 10%).

We also do not compensate for the different average weights of the vehicles (though the MOVES VSP bins scale emissions with mass).

For each test cycle from Sanders et al. (2003) and Garg et al. (2000), the following figures show how we went from the measured results to emission rates of g/hour at various deceleration speeds. Sanders et al (2003) used three measurement techniques, a filter, an Electrical Low Pressure Impactor (ELPI), and a Micro-Orifice Uniform Deposition Impactor (MOUDI). While all three measurement techniques produced similar results, we show all here. Test results are shown for the UDS, AMS and wind tunnel tests from Sanders, as well as the Garg analysis.

Figure 2-1 – UDP results

Test	brake lining	PM10 emiss.	(mg/stop/brake)	
UDP		filter	ELPI	
	low metallic	6.9	7.0	
	semi-metallic	1.7	1.7	
	Non-asbestos	1.1	1.5	
Average/stop/brake		3.2	3.4	
Avg. /veh		9.7	10.2	
deceleration =			**0.0012**	**km/s2**
avg. brake time in secs =			13.5116	secs
avg . emissions in mg/ stop =			9.95	mg
emission rate for the UDP test =			**2.65**	**gms/hr**

Figure 2-2 – Wind Tunnel results

Test	brake lining	PM10 emiss.	(mg/stop/brake)	
Tunnel		filter*	ELPI	MOUDI
	low metallic	44	45	40
deceleration=			**0.0018**	**in km/s^2**
Initial Velocity V(0) =			0.02667	in km/s
avg. brake time in sec =V(0)/dec			14.8148	
avg. emissions in mg/stop =			129.00	mg/stop
emision rate for the wind tunnel test=			**31.4**	**gms/hr**

Figure 2-3 – AMS results

Test	brake lining	PM10 emiss.	(mg/stop/brake)	
AMS		filter	ELPI	
	low metallic	800	70	
	semi-metallic	510	63	
	Non-asbestos	550	92	
	Average=	620	75	
	Avg/veh rate =	1116	135	

deceleration =	0.0079	in km/s^2
Initial Velocity V(0) =	0.0278	in km/s
avg. break time in sec =V(0)/dec	3.5162	
avg. emissions in mg/stop for PM 10=	1116	mg/stop
emision rate for PM10 for the AMS test=	**1142.6**	**gms/hr**
avg. emissions in mg/stop for PM 2.5=	135.0	
emision rate for PM2.5 for the AMS test=	**138.2**	**gms/hr**

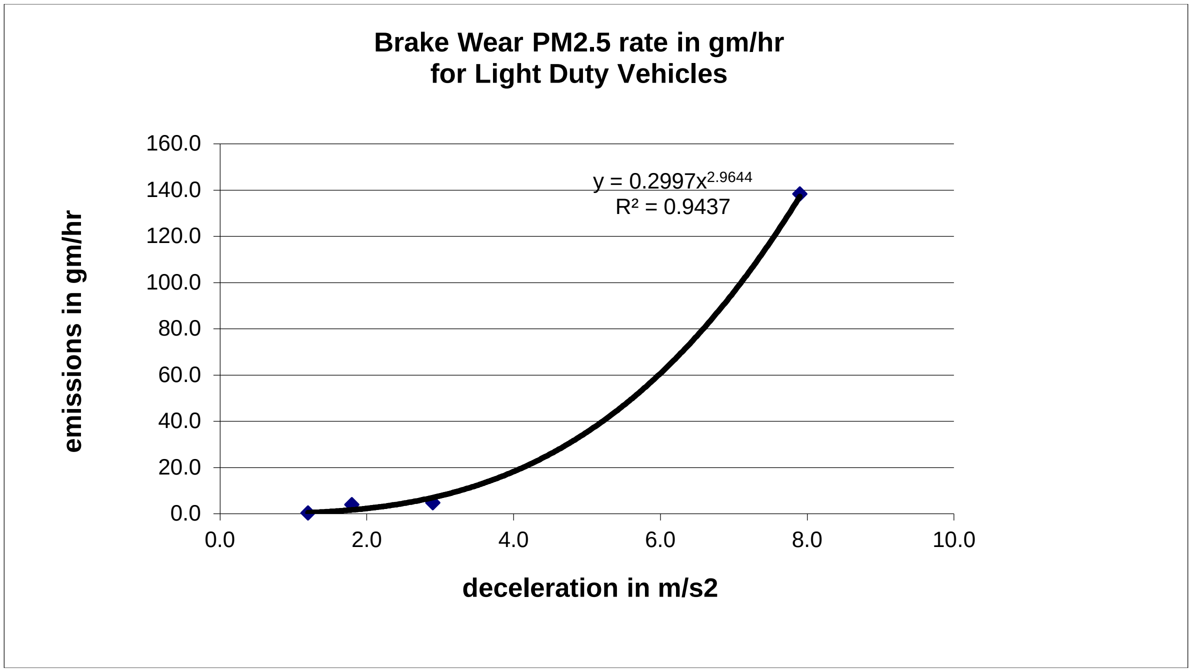
Figure 2-4 – Garg results

Test	brake lining	PM10 emiss.*	PM2.5**	(mg/stop/brake)
avg. over all temp.	semi-metallic #1	1.85	1.35	
	semi-metallic #5	0.82	0.60	
	NAOS #2	2.14	1.57	
	NAOS #3	0.89	0.66	
	NAOS#7	1.41	1.03	
	Grand Avg. =	1.42	1.04	mg/stop

deceleration =	0.00294	in km/s^2
Initial Velocity V(0) =	0.0139	in km/s
avg. break time in sec =V(0)/dec	4.7241	
avg. emissions in mg/stop for PM10 =	1.42	mg/stop
emision rate for PM10 for theGM test=	**1.08**	**gms/hr**
avg. emissions in mg/stop for PM2.5 =	1.04	mg/stop
emision rate for PM2.5 for the test=	**0.79**	gms/hr

We used these four data points to fit an exponential curve determine the emission rate at different speeds. The AMS test, at higher speed, has significant influence on results at rapid deceleration. Additional high speed tests could be used for future refinement of this data.

Figure 2-5



2.2.2 Activity

In the previous section, we determined the rate of particulate matter emissions during braking in units of grams per hour as a function of speed for a light-duty vehicle. However, for MOVES, we also need to determine the frequency of different levels of braking. The MOVES vehicle specific power (VSP) bins are relatively coarse for braking,[8] in that there is only a single braking operating mode for each speed category (Figure 2-6 – VSP Bins). Additionally, each of these deceleration operating modes include some cruise and coasting operation, where the throttle is closed (or nearly closed), but the brakes are not applied. Therefore, the emission rate assigned to this bin needs to contain the appropriate average rate including the mix of driving and deceleration frequencies, including decelerations that do not include braking.

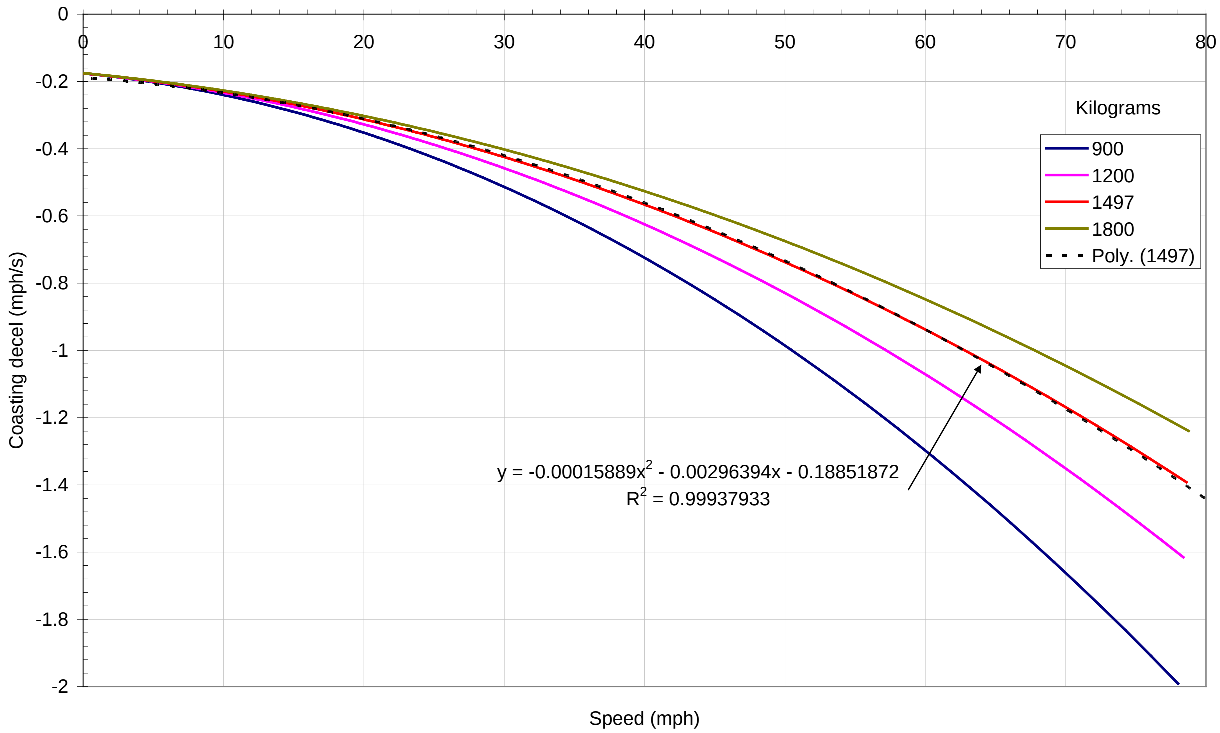
Figure 2-6 – VSP Bins

<table>
<tr><th rowspan="2">VSP Class (kW/tonne)</th><th colspan="3">Speed Class (MPH)</th></tr>
<tr><th>1-25</th><th>25-50</th><th>50+</th></tr>
<tr><td>30+</td><td rowspan="7">16</td><td>30</td><td>40</td></tr>
<tr><td>27-30</td><td rowspan="2">29</td><td rowspan="2">39</td></tr>
<tr><td>24-27</td></tr>
<tr><td>21-24</td><td rowspan="2">28</td><td rowspan="2">38</td></tr>
<tr><td>18-21</td></tr>
<tr><td>15-18</td><td rowspan="2">27</td><td rowspan="2">37</td></tr>
<tr><td>12-15</td></tr>
<tr><td>9-12</td><td>15</td><td>25</td><td rowspan="2">35</td></tr>
<tr><td>6-9</td><td>14</td><td>24</td></tr>
<tr><td>3-6</td><td>13</td><td>23</td><td rowspan="3">33</td></tr>
<tr><td>0-3</td><td>12</td><td>22</td></tr>
<tr><td><0</td><td>11</td><td>21</td></tr>
</table>

Operating mode where braking is assumed

We estimated the fraction of activity that is braking within each bin by first determining the coast down curve, then combining that with the activity fraction as seen in real-world driving surveys. The coastdown curves were generated using the Physical Emission Rate Estimator (PERE).[9] This was done by using the coastdown equations from PERE, and calculating the deceleration at each speed when the forward tractive power is zero. We assumed all activity below coastdown is braking. Figure 2-7 shows coastdown curves for cars of a variety of weights (and coastdown coefficients). The dotted curve is a typical coast down curve for this class of vehicle.

Figure 2-7 – Coastdown curves



The deceleration activity was determined from two real world instrumented vehicle studies: one from Kansas City and the other in Los Angeles. The Kansas City study was conducted by EPA and Easter Research Group (ERG) in 2005 to study real world driving activity and fuel economy on conventional as well as hybrid electric vehicles.[10] Over 200 vehicles were recruited, though for the current analysis, we only scrutinized the activity data of the conventional, or non-hybrid, population. The Los Angeles activity data was conducted by Sierra Research for the California Department of Transportation with both instrumented vehicles as well as chase car data[11,12,13]. The deceleration data was analyzed for both of these studies.

Table 2-7 shows the distribution of braking activity across speed and acceleration from both of these studies   The vast majority of braking occurs during minor slowdowns rather than full stops.

Table 2-7 – Activity Distribution

Decel (mph/s)	LA urban	LA rural	KC	AVG
1	37%	27%	54%	40%
2	26%	28%	26%	27%
3	18%	20%	13%	17%
4	10%	12%	5%	9%
5	6%	8%	1%	5%
6	2%	2%	0%	1%
7	1%	1%	0%	1%
8	0%	0%	0%	0%
9	0%	0%	0%	0%
10	0%	0%	0%	0%
11	0%	0%	0%	0%
12	0%	0%	0%	0%
13	0%	0%	0%	0%
14	0%	0%	0%	0%

2.2.3 Emission Rate for Light Duty vehicles

The emission rate curve was combined with activity discussed above to get MOVES rates for light duty vehicles. This gives a braking emission rate (gram per hour).

MOVES has brakewear emissions in op-modes 0,1,11,21,33. The brake emission rate is therefore weighted by the amount of braking activity in each bin. These braking fractions were derived using PERE as discussed above and are shown in the table below.

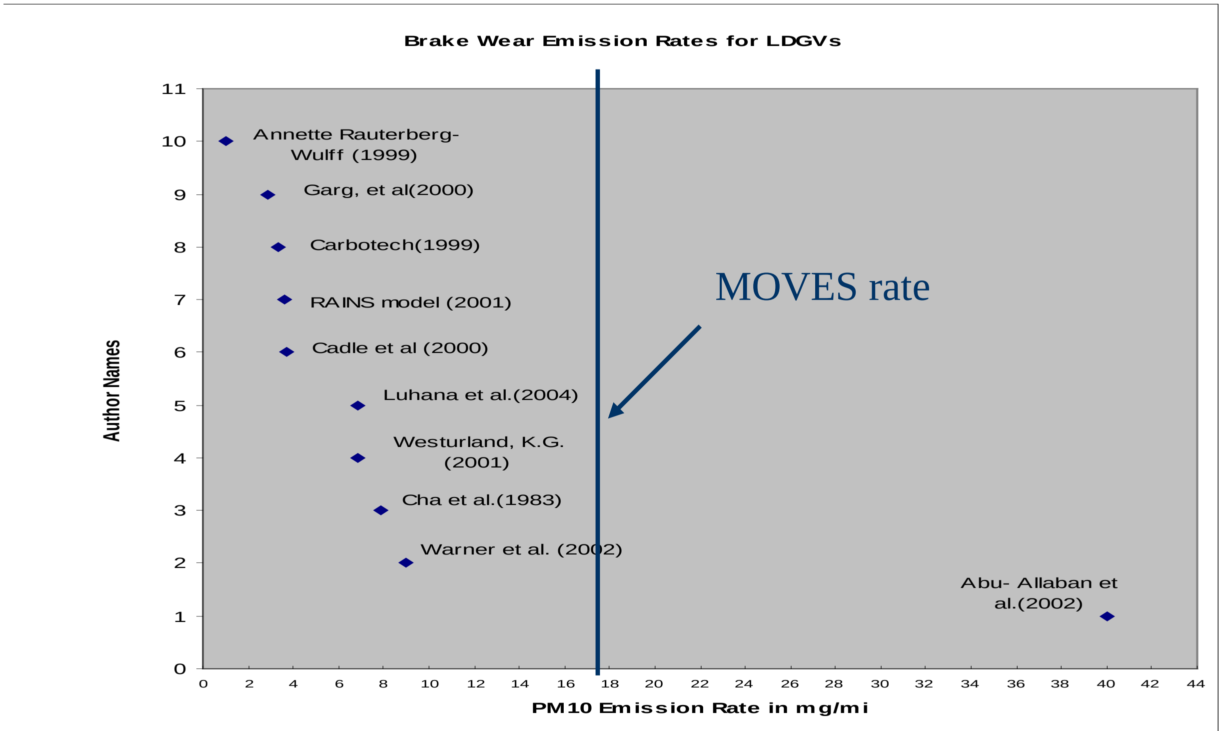
Table 2-8 – Fraction of Activity in VSP bin that is braking

	Compact	Mid-size	SUV	mddt	tractor
wgt (kg)	900	1497	1800	13517	22680
Cr0 (rolling resistance)	0.008	0.008	0.008	0.01	0.01
Cd (drag coeff)	0.32	0.35	0.36	0.44	0.44
A (frontal area m^2)	2	2.25	2.5	0.67	8.6397
vsp bin					
0	0.997	1	1	1	1
1	0.0437	0.0437	0.0437	0.0384	0.016
11	0.996	0.996	0.996	1.000	1
12	0	0	0	0.017	0.013
21	0.890	0.913	0.931	1.000	1.000
22	0.000	0.000	0.000	0.044	0.030
33	0.226	0.293	0.311	0.253	0.154

Using the activity from above, the FTP based emission rate (for passenger vehicles) is 0.21 g/hr PM2.5 (2 mg/mi), and 1.77 g/hr PM10 (20 mg/mi). For MOVES (based on real-world) , the emission rate (avg of KC and LA) is 0.56 g/hr PM2.5 (2.2 mg/mi) and 4.66 g/hr PM10 (17.6 mg/mi).

This emission rate is compared to the previous studies in the figure below.

Comparison of MOVES to other studies



2.2.4 Brake Wear Emissions for Heavy Duty Vehicles

In order to estimate brake wear emission factors for heavy-duty vehicles, results from a top-down study performed by Mahmoud Abu-Allaban et al. (2003) were used.[14] The study was performed at roadside locations in Reno, Nevada and Durham, North Carolina where intensive mass and chemical measurements were taken. In the above study, PM2.5 brake wear emission rates for heavy duty vehicles ranged from 0 to 15mg/km (0 to 24.13) mg/mi
The estimated emission factors for all other categories of vehicles except motor cycles were derived by ratioing to the vehicle class weight. Motorcycles were assigned a factor of 0.28 mg/mi, half that of an LDGV.

Table 2-2 – Scaling to other vehicle class.

	regclasswt in lbs.*	regclassid	wt. ratio	mg/mi	gms/hr**
MC		10	0.5	0.4	0.28
LDGV	8000	20	1	0.80	0.56
LDT	13,474	30	1.7	1.35	0.94
HD<= 14k	12,358	41	1.5	1.24	0.87
HD>14k	20,575	42	2.6	2.07	1.44
LHDD	14,404	45	1.8	1.45	1.01
MHDD	29,808	46	3.7	3.00	2.09
HHDD	59,369	47	7.4	3.49	4.16
Urban Bus	30,000	48	3.8	3.02	2.10

2.2.5 PM10/PM2.5 Brake Wear Ratio

MOVES stores PM2.5 brake wear emission rates by operating mode bin, than estimates PM10 emission rates by applying a PM10/PM2.5 ratio. The PM10/PM2.5 ratio is derived from the assumptions previously stated that the fraction of particles below PM10 is 0.80, and the fraction of particles below PM2.5 is 0.1. These assumptions result in a PM10/PM2.5 ratio of 8. Where no PM2.5 values were reported, we calculated PM2.5 from PM10 emission rates using this fraction.

3 Tirewear

3.1 Introduction

Tires are an essential part of any vehicle and the number and size of tires increase with the size of the vehicle. Contact between tires and the road surface causes the tires to wear, with the rate dependent on a variety of factors. Heavy braking and accelerating (including turning) increases tire wear.

EPA’s previous estimates of tire wear are contained in the PART5 model, and are emission rates of 0.002 grams per mile per wheel. Two LDV studies from the 1970s are the basis for these emission rates. The PART5 emissions factors are based on tests of older biased-ply tires rather than modern tire technologies, and in the National Resource Council report on the MOBILE model, are suggested to be out of date.[15]

Tire wear occurs through frictional contact between the tire and the road surface. In addition to frictional processes, tires are affected by heat and also through their contact with water on the road. Friction causes small and larger particles to wear from tire, which are then either released as airborne particulates, deposited onto the road surface or retained in the wheel hub temporarily or permanently until washed off. The rate at which tires wear is dependent upon a combination of factors such as route and style of driving, road surface, seasonal influences, vehicle characteristics and tire composition.

The route and style of driving determine the amount of acceleration. The acceleration of the vehicle determines the forces applied to the tire, and includes turning. Tire wear due to tire/road interface is determined by and is directly proportional to these forces.[16]The road surface causes friction and abrasion and therefore the roughness of the surface affects the wear rate by a factor of 2-3 times.[17] The season results in temperature, humidity and water contact variations. Wear rates are lower in wet compared to dry conditions.

The key influences of vehicle characteristics on tire wear are the weight, suspension and steering geometry. Axle geometry changes result in uneven wear across the tire width. The type of tire influences the wear significantly. In particular, the shape of the tire (determined by stiffness), the rubber volume (tread pattern), and the characteristic of the tire (rubber type etc.). Tire design and composition are other significant contributing factors. Highway geometry is also a key factor with rise and fall in roads resulting in increased tread wear. As a consequence of different manufacturing specifications, different brands of tires wear at different rates.

Retreads are considered to wear more than new tires. Wear rate studies on tire fleets reported in Bennett & Greenwood (2001) indicated that retreads had only about 75% of the tire tread volume that new tires had. Cenek et al. reported that 20% of New Zealand passenger tire sales were retreads and that retreads made up 75% of the tire tread in a sample of buses in the New Zealand fleet.[18]

According to the literature, the most straightforward method for determining tire wear is the periodic measurement of tread depth. However, variations in the extent of wear across the tire and irregularities in tire shape could lead to inaccurate measurements. Determining tire weight loss is a more sensitive approach than the measurement of tire depth, though care must be taken to avoid errors due to damage to tires as a result of their removal from the vehicle and hubs, and material embedded in the tire. To minimize damage to the tire, Lowne weighed both the wheel and tire simultaneously after the wheel was brushed and stones embedded in the tire were removed.[19]

Wear rates for tires have typically been calculated based on tire lifetime (in kilometers traveled), initial weight and tread surface depth. Tire wear occurs constantly for moving vehicles, but may be significantly higher for cars which tend to brake suddenly or accelerate rapidly. Tire wear rates have been found to vary significantly between a wide range of studies that have been carried out.[20]

Speed variation is an important factor as well. Carpenter & Cenek have shown that the effect of speed variation is highest at low speeds as a result of inertial effects and effective m9ass. [21] They also examined lateral force effects on tires and assessed tire wear on routes of different amounts of horizontal curvature and found that there was little variation.

Tire abrasion is difficult to simulate in the laboratory, since the nature of the road and driving conditions influence wear rates in urban environments. That being said, Hildemann et al. determined the chemical composition of tire wear particles using a rolling resistance testing machine at a tire testing laboratory over a period of several days.[22] Rauterberg-Wulff determined particle emission factors for tire wear using modeling in combination with measurements conducted in the Berlin-Tegel tunnel.[23]

Tire wear rates have been measured and estimated for a range of vehicles from passenger cars to light and heavy duty trucks and results reported by authors as either emission per tire or per vehicle. A range of tire wear rates from 64-360 mg/vehicle/km has been reported in the literature. Much of the variability in these wear rates can probably be explained by the factors mentioned above. These studies made no distinction between front and rear tires, even though they can wear at different rates.[24]

Table 3-1 - Tire wear rates found in the literature

Source	**Remarks**	**rate in mg/vkm**
Kupiainen,K.J. et al(2005)[25]	Measured tire wear rate	9 mg/km - PM10 2 mg/km - PM2.5
Councell,T.B. et al (2004) U.S. Geological Survey[26]	Calculated rate	50
Warner et al. (2002)[27]	Average tire wear for a vehicle	97
Kolioussis and Pouftis (2000)[28]	Average estimated tire wear	40
EMPA (2000)[29]	Light duty vehicle tire wear rate	53
	Heavy duty vehicle tire wear rate	798
SENCO (Sustainable Environment Consultants Ltd.) (1999)[30]	Light duty vehicle tire wear rate	53
	Wear rate for trucks	1403
Legret and Pagotto (1999a)	Estimated rate for light duty vehicles	68
	Estimated rate for heavy vehicles (>3.5t)	136
Baumann (1997)[31]	Passenger car tire wear rate	80
	Heavy duty vehicle tire wear rate	189
	Articulated lorry tire wear rate	234
	Bus tire wear rate	192

Garben (1997)[32]	Passenger car tire wear rate	64
	Light duty vehicle tire wear rate	112
	Heavy duty vehicle tire wear rate	768
	Motorbike tire wear rate	32
Gebbe (1997)[33]	Passenger car tire wear rate	53
	Light duty vehicle tire wear rate	110
	Heavy duty vehicle tire wear rate	539
	Motorbike tire wear rate	26.4
Lee et al (1997)[34]	Estimated tire wear rate	64
Sakai,H (1995)	Measured tire wear rate	0.184
Baekken (1993)[35]	Estimated tire wear rate	200
CARB (1993)	Passenger car tire wear rate	120
Muschack (1990)	Estimated tire wear rate	120
Schuring and Clark (1988)[36]	Estimated tire wear rate	240-360
Pierce,R.N. (1984)	Estimated tire wear rate	120
Malmqvist (1983)[37]	Estimated tire wear rate	120
Gottle (1979)[38]	Estimated tire wear rate	120
Cadle et al. (1978)[39]	Estimated tire wear rate	4
Dannis (1974)[40]		90

3.2 Methodology

This report primarily utilizes data from work published by Luhana et al.(2004) wherein wear loss rates for tires have been determined gravimetrically for in-service cars.[41] At the time of this analysis, this paper was both a recent and comprehensive study. The authors weighed car tires at two-month intervals, and asked drivers to note the details of each trip undertaken. Five test vehicles (labeled A-E) were selected for the tests. Of these vehicles A, B, C and E were front-wheel drive vehicles. The predominant road type used by vehicles A and B were motorways, by vehicle D it was rural roads and motorways and by vehicle C it was suburban roads. Vehicle D was excluded from the study since it was a RWD vehicle. The selection of vehicles was based primarily on driving conditions, as defined by the main type of road used by the owner and annual distance driven.

Table 3-2: Test Vehicles Weight Loss from Tires and Average Speed

Car	Model	Test	Mean Tire weight loss (mg/km)			
		Period	Front	Rear	Total	Avg. sped (km/h)
A	Audi A3	1	20.24	9.13	58.7	93.3
		2	20.85	12.52	66.8	90.6
		3	13.15	6.93	40.2	93.9
		4	17.18	8.63	51.6	92.7
B	Ford Mondeo	1	29.76	8.72	77.0	65.4
		2	26.22	9.08	70.6	71.9
		3	19.01	4.00	46.0	74.4
		4	29.71	7.04	73.5	70.2

C	Peugeot 205	1	31.37	4.38	71.5	44.5
		2	32.75	13.17	91.8	42.9
		3	28.42	6.43	69.7	48.9
		4	52.70	1.63	108.7	50.4
E	Vauxhall Cavalier	1	37.03	10.51	95.1	61.3
		2	26.55	10.87	74.8	65.8
D	Ford Sierra	1	49.94	46.10	192.1	59.6
		2	49.91	47.29	194.4	63.6

Results from Luhana's study indicated that the lowest tire wear rates (56 mg/vkm and 67 mg/vkm respectively) were for vehicles A and B that were driven predominantly on motorways. Vehicles C and E had very similar wear rates (around 85 mg/vkm) although these vehicles tended to be driven on different roads. Based on the wear rates from the four front-wheel drive cars alone, the study concluded that the average wear rate is around 74 mg/vkm. This value seems to lean towards the lower end of the range of wear rates reported in the literature.

The data presented in the tables below includes calculations for the distances completed by each vehicle between successive tests, the estimated average trip speeds and predominant road types for the equivalent periods. It was assumed that the weight of the wheels remained constant during the tests, and any weight loss was due solely to the loss of tire rubber during driving.

Table 3-3: Data used for the analysis

		Front-wheel Drive vehicles only				
	Avg. trip speed	Tire Wt. Loss		total wt. loss	total wt. loss	avg. speed
units	km/hr	Front mean (gms/km)	Rear Mean (gms/km)	gms/km	gms/mi	in mi/hr
test1-A	90.3	0.0202	0.0092	0.0589	0.0947	56.1
test2-A	90.6	0.0209	0.0126	0.0669	0.1076	56.3
test3-A	93.9	0	0.0069	0	0	58.4
test4-A	92.7	0.0172	0.0086	0.0516	0.083	57.6
test1-B	65.4	0.0298	0.0087	0.077	0.1239	40.6
test2-B	71.9	0.0262	0.0091	0.0705	0.1135	44.7
test3-B	74.4	0.019	0.004	0.0461	0.0742	46.2
test4-B	70.2	0.0297	0.007	0.0735	0.1183	43.6
test1-C	44.5	0.0312	0.0047	0.0718	0.1155	27.7
test2-C	42.9	0.0331	0.0132	0.0925	0.1489	26.7
test3-C	48.8	0.0284	0.0064	0.0697	0.1121	30.3
test4-C	50.4	0.0532	0.0045	0.1153	0.1855	31.3
test3-E	61.3	0.037	0.0104	0.0948	0.1525	38.1
test4-E	65.8	0.0265	0.0109	0.0749	0.1205	40.9

Note: Vehicles A and B were driven mainly on motorways (freeways)
Vehicle C was driven on Suburban Roads and
Vehicle E was driven mostly on Rural roads

Using the above data on average speed and total weight loss an exponential regression curve was fitted which was characterized by an R^2 value of 0.43. The actual and predicted values are presented in Figure 3-1 and Figure 3-2.

A weak negative correlation is shown between tire wear and average trip speed , with wear being around 50% higher at an average speed of 40 km/h (dominated by urban driving) than at an average speed of 90 km/h (dominated by motorway driving).

Figure 3-1: Relationship between tire weight loss and mean trip speed between tests

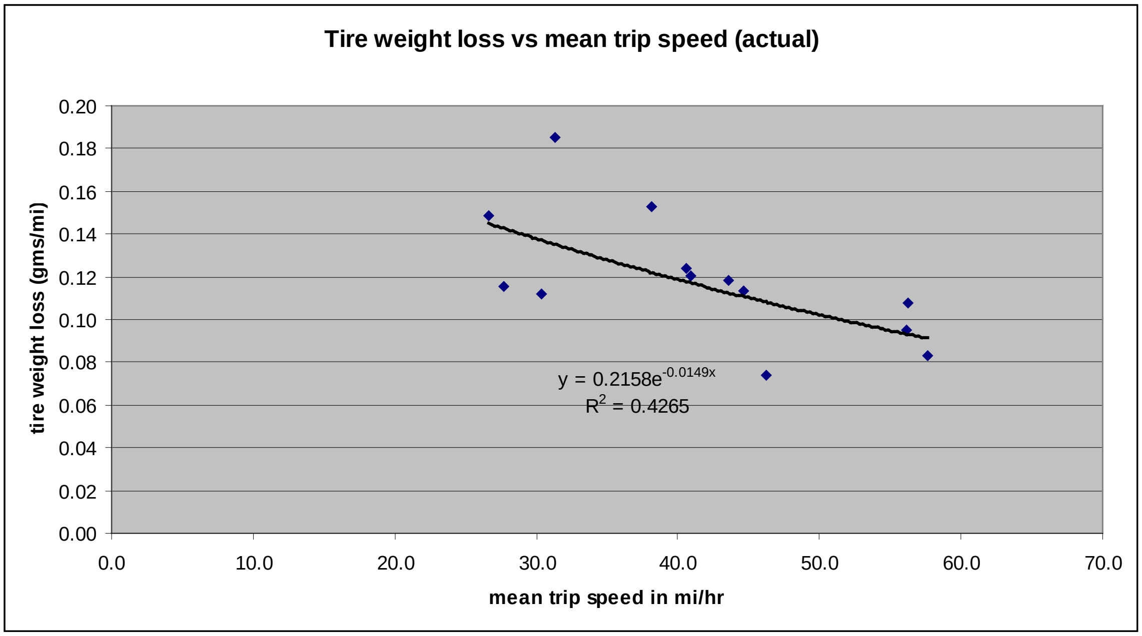
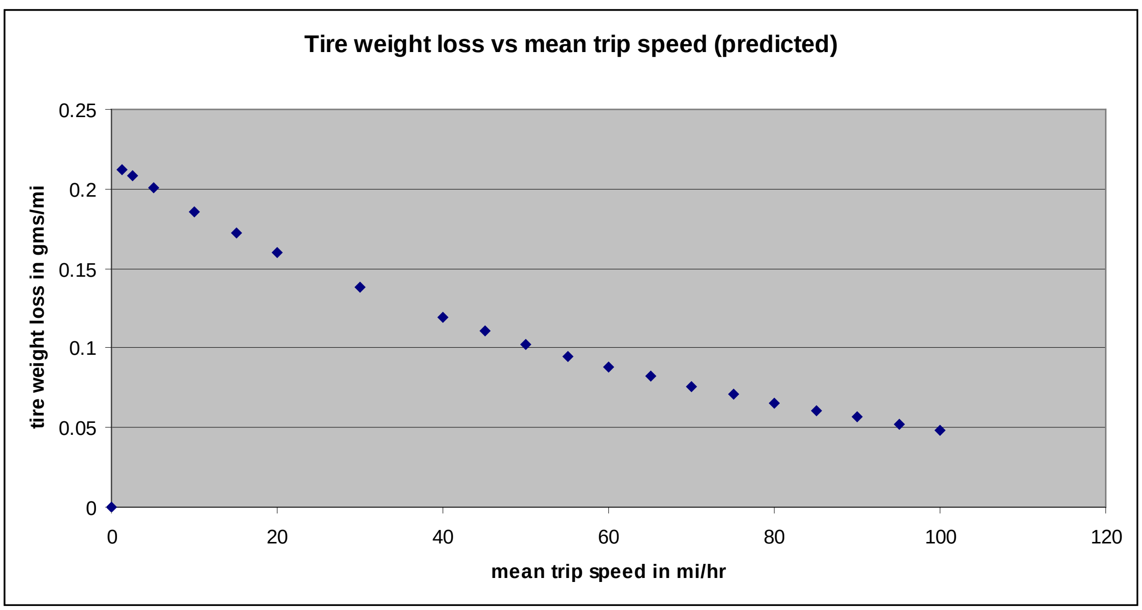


Figure 3-2: Predicted values using an exponential fit.



The shape of the curve deserves some discussion. It can be seen from the curve that the wear is maximum at zero speed and goes down as the speed goes up. This may seem counter-intuitive, however, it is important to note that the relationship does not take accelerations (and turning) into account. Much of the tirewear occurs at low speeds when the vehicle is accelerating from rest, or when the vehicle is braking hard to stop. A more improved relationship would be by VSP bin, however this data is not presently available. We have thus simplified the model to be based on speed at this time.

The predicted values as determined above are for passenger cars (LDVs). To determine tire wear loss rates for other regulatory classes it was assumed that total tire wear is dependent upon the number of tires on the vehicle which in turn is a function of the number of axles per vehicle by vehicle class. The data was found to be available in the Vehicle Inventory and Use Survey (VIUS 2002) data base. This data enabled the calculation of tires per vehicle for each of the six truck classes and thereby tire-wear losses for the different truck categories (regulatory classes) were determined. The average number of tires per truck is given in Table 4 below.

Table 3-4 - Average Number of Tires per Truck - 2002 VIUS Survey

RegClassID	regclass name	Total Vehicles	Total # Tires	Tires Per Vehicle
10	MC	N/A	N/A	2.0
20	LDV	N/A	N/A	4.0
30	LDT	519,203,076,188	2,098,863,966,734	4.0
41	LHD<=14K	3,643,242,030	20,120,114,684	5.5
42	LHD45	15,626,996,979	93,447,330,500	6.0
46	MHDD	10,781,216,281	74,960,221,824	7.0
47	HHDD	18,657,394,114	277,811,528,442	14.9
48	Urban Bus			8.0

* Note: Tires per vehicle for LDT is the same as that for LDV

Table 5 above gives the emission rates in g/mi by average bin speed for all regulatory classes. The wear factors above will be dependent on the number of axles and the load, and so a wide range of values is to be expected. Table 6 below is the PM $_{2.5}$ equivalent in gm/hr.

The literature indicates that probably less than 10% of car tire wear is emitted as PM10 under 'typical' driving conditions but the proportion could be as high as 30% (Boulter2005a). According to Luhana, PM_{10} appears to be released from tires at a rate of between 4 and 6 mg/vkm for passenger cars. This suggests that generally between around 1% and 15% by mass of passenger car tire wear material is emitted as PM_{10}, but much higher proportions have been reported in some studies. According to Kupiainen et al (2005) PM2.5 fractions were on average 15% of PM10. The results of Kupiainen were used by Boulter(2005a) to estimate tire PM10 emission factors for LDVs.

Assuming 8% of tire wear to be emitted as PM10 and 15% of PM10 as PM2.5, we then have Table 6 below that gives PM2.5 rates in g/hr to be used in MOVES.

Table 3-5 – PM2.5 Tire wear emissions (g/mi)by Avgbinspeed and RegclassID

SpeedBinID	avgBinSpeed	OpModeID	10	20	30	41	42	46	47	48
1	1.25	401	0.106	0.212	0.212	0.292	0.317	0.368	0.789	0.424
2	5	402	0.100	0.200	0.200	0.277	0.299	0.348	0.746	0.401
3	10	403	0.093	0.186	0.186	0.257	0.278	0.323	0.692	0.372
4	15	404	0.086	0.173	0.173	0.238	0.258	0.300	0.642	0.345
5	20	405	0.080	0.160	0.160	0.221	0.239	0.278	0.596	0.320
6	25	406	0.074	0.149	0.149	0.205	0.222	0.258	0.553	0.297
7	30	407	0.069	0.138	0.138	0.191	0.206	0.240	0.514	0.276
8	35	408	0.064	0.128	0.128	0.177	0.192	0.223	0.477	0.256
9	40	409	0.059	0.119	0.119	0.164	0.178	0.207	0.443	0.238
10	45	410	0.055	0.110	0.110	0.152	0.165	0.192	0.411	0.221
11	50	411	0.051	0.102	0.102	0.141	0.153	0.178	0.381	0.205
12	55	412	0.048	0.095	0.095	0.131	0.142	0.165	0.354	0.190
13	60	413	0.044	0.088	0.088	0.122	0.132	0.153	0.329	0.177
14	65	414	0.041	0.082	0.082	0.113	0.122	0.142	0.305	0.164
15	70	415	0.038	0.076	0.076	0.105	0.114	0.132	0.283	0.152
16	75	416	0.035	0.071	0.071	0.097	0.106	0.123	0.263	0.141

3.2.1 PM10/PM2.5 Tire Wear Ratio

MOVES stores PM2.5 tire wear emission rates by operating mode bin, than estimates PM10 emission rates by applying a PM10/PM2.5 ratio. MOVES applies a PM10/PM2.5 ratio of 6.667, which is consistent with the particle size distribution of tire wear measured by Kupianen et al. (2005).

Appendix A- Review of literature on brake wear		
Luhana,L.;Sokhi,R.;Warner,L.;Mao,H; Boulter,P;McCrae,I.S.;Wright,J and Osborn,D,"Non-exhaust particulate measurements:results," *Deliverable 8 of the European Commission DG TrEn, 5th Framework PARTICULATES project , Contract No.* 2000 -RD.11091, Version 2.0 , October 2004.	2004	Non-exhaust particle research was conducted in the Hatfield road tunnel. Combined tire and break wear emissions for PM_{10} from LDVs and HDVs in the tunnel were found to be 6.9mg/vkm and 49.7mg/vkm respectively. These emission factors from the Hatfield Tunnel Study appears to be at the lower end of the range of values reported elsewhere. The report also includes a literature review which examines the state of the art in the field. Tire wear and brake wear rates are listed below.
Sanders, Paul G.;Xu, Ning ;Dalka, Tom M.; and Maricq, M. Matti, "Airborne Brake Wear Debris: Size Distributions, Composition, and a Comparison of Dynamometer and Vehicle Tests",*Environ. Sci. Technol.,* 37,4060-4069,2003	2003	A brake wear study was performed using seven brake pad formulations that were in high volume use in 1998. Included were low-metallic,semi-metallic and non-asbestos organic (NAO) brakes.The quantity of airborne PM generated by automotive disk brakes was measured on a brake dynamometer that simulated : urban driving (low velocity,low g) and the Auto Motor und Sport (AMS,high velocity, high g). Airborne fractions from the low-metallic and semi-matallic linings were 5 and 1.5 times higher than the NAO lining.
L.R.Warner; R.S. Sokhi; L.Luhana ; P.G. Boulter; and I. McCrae,"Non-exhaust particle Emisions from Road Transport", *Proceedings of the 11th International Symposium on Transport and Air Pollution*, Graz, 2002.	2002	The paper presents preliminary results of gravimetric determination of tire and brake wear for cars, and chemical analysis of ambient particle samples for source identification using Inductively Coupled Plasma (ICP) spectrometry. Results suggest that the average loss rates of tire and brake material are 97 and 9 mg/vkm respectively. The ICP analysis shows a high relative abundance of Ba,Sb,Zr and Sr for brake and Zn for tire material. The chemical analysis also suggests that for tire wear it is much more difficult to use metal concentrations as tracers.
Abu-Allaban, M.;Gillies, J.A.;Gertler,A.W.;Clayton ,R.; and Proffitt,D., "Tailpipe, re-suspended road dust, and brake wear emission factors from on-road vehicles," *Atmospheric Environment*, 37(1),5283-5293,2002.	2002	Intensive mass and chemical measurements were performed at roadside locations to derive brake-wear emission factors from in-use vehicles. PM_{10} emission rates for LDSI vehicles ranged from 0 to 80 mg/vkm and for HDVs from 0 to 610 mg/vkm. The $PM_{2.5}$ emissions ranged from 0 to 5mg/vkm for LDSI vehicles and from 0 to 15mg/vkm for HDVs. Emissions from brake wear were highest near motorway exits.
Lukewille,A.;Bertok,I.;Amann, M., Cofala,J.;Gyarfas,F.;Heyes,C.;Karvosenoja,N.;Klimont Z.; and Schopp, W., " A framework to estimate the potential and costs for the control of fine particulate emissions in Europe",*IIASA Interim Report IR-01-023*,Laxenburg, Austria,2001.		

Westerlund ,K.G.," Metal emissions from Stockholm traffic –wear of brake linings ",*The Stockholm Environment and Health Protection Administration*, 100,64,Stockholm,Sweden,2001.	2001	Westerlund estimated the amount of material lost due to brake wear from passenger cars and heavy goods vehicles. The PM_{10} emission factors were determined to be 6.9 and 41.2mg/vkm for LDVs and HDVs respectively.
Garg, B.D.; Cadle, S.H.; Mulawa,P.A.; Groblicki, P.J.;Laroo,C.; and Parr,G.A., "Brake wear particulate matter emissions", *Environmental Science & Technology,* 34(21),4463,2000b.	2000	A brake wear study was performed using seven brake pad formulations (non-asbestos) that were in high volume use in 1998. Brakes were tested on a brake dynamometer under four wear conditions. The brake application was designed to simulate real world events by braking from 50km/h to 0km/h at a deceleration of 2.94 m/s^2. The estimated range of PM emission rates for small vehicles to large pickup trucks are 2.9 - 7.5 mg/vkm and 2.1 – 5.5 mg/vkm for PM_{10} and $PM_{2.5}$ respectively.
Annette Rauterberg-Wulff , "Determination of emission factors for tire wear particles up to 10um by tunnel measurements", *Proceedings of 8th International Symposium on Transport and Air Pollution,* Graz, 1999.	1999	PM_{10} emission factors were determined for tire and brake wear using receptor modeling in combination with measurements conducted in the Berlin-Tegel tunnel. Tire wear emission factors for LDVs and HGVs in the tunnel was calculated to be 6.1 mg/vkm and 31 mg/vkm. For brake wear it was 1.0 and 24.5 mg/vkm respectively.
Carbotech, "PM_{10} Emissionsfaktoren:Mechanischer ………",*Arbeitsunterlage,* ,17,1999	1999	Cited in Lukewille et al.(2001). The PM_{10} brake wear emission factor for LDVs was determined to be 1.8 mg/km and for HDVs it was 3.5 mg/vkm.
Cha,S.; Carter,P.; and Bradow, R.L., "Simulation of automobile brake wear dynamics and estimation of emissions,"*SAE Transactions Paper*,831036, Society of Automotive Engineers, Warrendale, Pennsylvania,1983	1983	Particulate emissions from asbestos-based brakes from automobiles were measured under conditions simulating downtown city driving. The report presents a systematic approach to simulating brake applications and defining particulate emissions. Based on the 1.6:1.1 wear ratio between disc and drum brakes,the estimated airborne particulate (PM_{10}) emission rate was estimated to be 12.8mg/vmi or 7.9 mg/vkm.

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